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October 17, 2003

Corrosion/2004
New Orleans, LA, United States
March 28, 2004 through April 1, 2004

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03October2003

Paper04551tobepresentedattheNACEInternational,CORROSION/04ConferenceinNewOrleans,
LA28Marchto01April2004

SUSCEPTIBILITY OF WELDED AND NON-WELDED TITANIUM ALLOYS TO ENVIRONMENTALLY ASSISTED CRACKING IN SIMULATED CONCENTRATED GROUNDWATERS

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ABSTRACT

The engineering barriers for the nuclear waste repository at Yucca Mountain include a double walled container and a detached drip shield. The material selected to construct the drip shield will be Titanium Grade 7 (TiGr7 or R52400). TiGr7 is highly resistant to corrosion and consequently it is widely used to handle aggressive industrial environments. The model for the degradation of the engineering barriers includes three modes of corrosion, namely general corrosion, localized corrosion and environmentally assisted cracking (EAC). The objective of the current research was to characterize the susceptibility of three titanium alloys to EAC in several environmental conditions with varying solution composition, pH and temperature. The susceptibility to EAC was evaluated using constant deformation (deflection) U-bend specimens in both the non-welded and welded conditions. Results show that after more than five years exposure in the vapor and liquid phases of alkaline (pH~10) and acidic (pH~3) multi-ionic environments at 60°C and 90°C, most of the specimens were free from EAC. The only specimens that suffered EAC were welded TiGr 12 (R53400) exposed to liquid simulated concentrated water (SCW) at 90°C.

Keywords: high-level nuclear waste, titanium alloys, R52400, R52402, R53400, environmentally assisted cracking, U-bend, welded specimens, temperature, simulated acidified water (SAW), simulated concentrated water (SCW), simulated dilute water (SDW).

INTRODUCTION

The current waste package design for the Yucca Mountain Project consists of two concentric metal containers and a detached drip shield.^{1,2} Type 316L stainless steel (S31603) is the specified material for the internal barrier or shell of the container, to act as a shield to radiation and to provide mechanical integrity.

rity. Alloy 22 (N06022) is the candidate material for the external barrier or shell of the container. The primary purpose of the outer container is to provide protection against corrosion. Alloy 22 (N06022) was selected for this application because it is well known commercially for its excellent corrosion resistance in aggressive environments.³⁻⁷ Titanium grade 7 (TiGr7 or R52400) has been chosen to fabricate the detached drip shield. The presence of the drip shield would deflect early water seepage from the placement walls on the containers. In addition, this drip shield would deflect rock fall from the containers. Canada and Japan are also considering titanium as a candidate material to fabricate their nuclear waste containers, in a different application of that of Yucca Mountain.^{8,9}

TiGr7 belongs to a family of Ti alloys especially designed to withstand aggressive chemical environments. The superior corrosion resistance of Ti and Ti alloys is due to a thin, stable and tenacious oxide film that forms rapidly on Ti in air and water, especially under oxidizing conditions.¹⁰ Ti alloys have a broad range of application as corrosion resistant materials. This includes seawater, wet chlorine, chlorine-ated organic compounds and oxidizing acids (e.g. nitric and chromic acids).^{5,10,11} Some of the media in which Ti should not be used include hydrofluoric acid, dry chlorine and hot pure sulfuric acid solutions.¹² The family of Ti corrosion resistant alloys includes grades from 1 to 34.¹³ TiGr2 (R50400) is commercially one of the most popular grades. Other, more corrosion resistant grades, which are the focus of the current study, includes TiGr7 (R52400), TiGr16 (R52402) and TiGr12 (R53400) (Tables 1 and 2). These grades contain small amounts of alloying elements that improve the corrosion resistance of titanium in reducing conditions by a mechanism called the cathodic modification.¹⁴ TiGr7 contains 0.12-0.25% palladium (Pd), TiGr16 contains 0.04 -0.08% Pd and TiGr12 contains 0.2 -0.4% molybdenum (Mo) and 0.6 -0.9% nickel (Ni).¹³ In general, the corrosion resistance of TiGr7 is superior to that of TiGr12; however, this effect is more noticeable under reducing conditions due to the beneficial effect of Pd.⁵ Corrosion rate data for TiGr16 are scarce. Some Ti alloys may be susceptible to crevice corrosion under certain conditions; however, these alloys are practically immune to pitting corrosion in halide containing environments under most practical applications.¹⁰ It has been suggested that the susceptibility to crevice corrosion is due to the formation of low pH reducing solution under the occluded conditions, where the corrosion rate of Ti is higher than in oxidizing conditions.¹⁵⁻¹⁶ Halide and sulfate containing solutions may induce crevice corrosion in Ti at temperatures higher than 70°C.^{17,18} Bromide ions seem more aggressive than chloride ions for the passivity breakdown of Ti.¹⁹ Anodic polarizations of TiGr7 in chloride and fluoride containing solutions at 95°C have shown that the presence of fluoride produces significantly higher current densities above the corrosion potential.²⁰ The presence of fluoride may have also rendered TiGr7 more susceptible to crevice corrosion under anodic polarization.²⁰

Titanium and Ti alloys may suffer environmentally assisted cracking (EAC) such as hydrogen embrittlement (HE) and stress corrosion cracking (SCC). Embrittlement by hydrogen is a consequence of a desorption of atomic hydrogen by the metal to form hydrides.^{10,12,17,21-25} This may happen in service when the Ti alloy is coupled to a more active metal in an acidic solution.¹⁰ A critical concentration of hydrogen in the metal may be needed for HE to occur.²³ The few environments that can induce SCC in Ti are absolute (anhydrous) methanol, red fuming nitric acid and nitrogen tetroxide.^{10-11,17,22,26-27} A few percent of water in the environments mentioned above would inhibit the SCC in Ti.¹⁰

The susceptibility to stress corrosion cracking and hydrogen embrittlement of titanium and Ti alloys has been studied recently regarding its application for the Yucca Mountain repository. Roy et al. performed slow strain rate tests ($3.3 \times 10^{-6} \text{ s}^{-1}$) on smooth specimens of TiGr7 and TiGr12 in 5 wt% NaCl pH 2.7 at 90°C at the applied potentials between 0 V and -1.2 V (SSC).²⁸ They reported that for TiGr12 (R53400), as the potential decreased the reduction of area at rupture decreased from 40% at 0 V to approximately 15% at -1.2 V (SSC).²⁸ They attributed this behavior to a hydrogen embrittlement mechanism.

nism due to the formation of hydrides. Under the same tested conditions the reduction of area of TiGr7 (R52400) remained approximately constant at near 50%. Roy et al. reported that after straining, both TiGr7 and Gr12 exhibited shallow secondary cracks at all of the tested potentials.²⁸ Greene et al. calculated that the critical concentration of hydrogen to produce HE was higher in palladium containing titanium alloys (such as TiGr7) than for titanium alloys without palladium (such as TiGr12).²⁹ Greene et al. also anticipated that an enhanced passive corrosion rate of TiGr7 (for example in an environment containing fluoride ions) could produce enough hydrogen to reach the critical concentration in the metal to cause HE.²⁹ Pulvirenti et al. reported intergranular stress corrosion cracking (IGSCC) changing to transgranular stress corrosion cracking (TGSCC) on one U-bend specimen of TiGr7 exposed for 155 days in a solution containing 35,500 ppm chloride and 1900 ppm fluoride pH 6.5 at 105°C.³⁰ Young et al. reported stress corrosion cracking in TiGr7 specimens subjected to constant load tests in a concentrated groundwaters solution pH~10 at 105°C.³¹

Water that contact the drip shield are expected to be in the form of a multi-ionic solution. This solution may form through two different mechanisms: (1) Dripping from the drift wall and concentrating on the drip shield surface and (2) Deliquescence of salts (dust) that may accumulate on top of the drip shield during dry periods. In both cases, the aqueous solution would be concentrated. The groundwaters that are associated with the Yucca Mountain region have been well characterized.^{32,33} Table 3 shows the composition of a saturated zone water (from a well designated, J-13) from near the repository site. The well water, J-13, is near-neutral and bicarbonate-rich with significant concentrations of sulfate, nitrate, chloride, alkalis and alkaline earths ions. Table 1 also shows the composition of various laboratory-prepared, aqueous, concentrated electrolyte solutions in which testing was performed. These electrolyte solutions range from pH~3 to 10 and are designated as simulated acidified water (SAW), simulated concentrated water (SCW) and simulated dilute water (SDW).

The purpose of the present work was to determine the stress corrosion cracking resistance of TiGr7 after more than a 2.5-year exposure and TiGr16 and TiGr12 after more than a 5-year exposure in the above mentioned multi-ionic solutions at 60°C and 90°C using U-bend specimens.

EXPERIMENTAL

There are several different techniques that can be used in the laboratory to study the susceptibility of alloys to EAC. The techniques can be grouped by the way the mechanical stress is applied to the testing specimen. In order to better simulate the likely field behavior, the samples that are used for laboratory testing should reproduce closely the field conditions. The only mechanical stresses that may be present in the containers at the Yucca Mountain Site would be residual stresses due to fabrication or possible rock fall impact. Therefore, the specimens chosen for laboratory testing were U-bend specimens, which also contained residual stresses due to permanent deformation.

The studied nickel alloys included Titanium Grade 7 (R52400), Titanium Grade 16 (R52402) and Titanium Grade 12 (R53400). Table 2 shows the compositions of the studied alloys. The welded U-bend specimens had matching filler metal, that is, a wire of the same alloy was used to produce the welds (Table 2). In the designation of the specimens, the first letter corresponded to the type of alloy. Thus an initial letter N represents TiGr7, the letter F represents TiGr16 and the letter E represents TiGr12 (Table 1). The second letter in the designation represents the type of specimen, in this case the letter U represents U-bend. The third letter designates if the material for the U-bend was seamless wrought mill annealed (MA) (letter A) or had a weld seam (letter different from A) (Figure 1 and Table 4). These three

letters are followed by a three-digit serial number. Thus, FUE079 is the welded TiGr 16U -bend specimen number 79.

The U -bend specimens were machined from sheet stock. The specimens were tested in the as-machined condition, which corresponded to a root mean square (RMS) roughness of $32\text{ }\mu\text{-inch}$. The specimens were degreased in acetone before testing. The U -bend specimens were prepared using $3/4\text{-inch}$ ($\sim 19\text{ mm}$) wide and $1/16\text{-inch}$ ($\sim 1.6\text{ mm}$) thick strips according to ASTM G30. The resulting specimen had a constant nominal separation between both legs, or ends, of 0.5 inch ($\sim 13\text{ mm}$) secured by a bolt, which was electrically insulated from the specimen through ceramic zirconia washers. The total plastic deformation in the external outer fiber was approximately 12%. Single U -bends were produced using both wrought sheets and welded sheets. In the welded specimens, the weld was across the apex of the bend (Figure 1). The weld process was gas metal arc welding (GMAW) using filler metal and the seam had full penetration. Typical mechanical properties of MA sheet material are listed in Table 1. Table 2 lists the chemical composition of the sheet material and the filler metal used for the fabrication of the U -bend specimens.

The testing electrolyte solutions for the U -bend were solutions containing several ionic species. The volume of the electrolytes was approximately 1000 liters. Table 3 shows the composition of the multicomponent electrolyte solutions mentioned in this paper. Table 3 also shows the composition of the water from well J -13 at Yucca Mountain. The solutions used in this study are concentrated versions of J -13 water. The U -bend immersion tests were carried out at 60°C and 90°C . Approximately half of the specimens were exposed to the liquid phase of the solution and the other half to the vapor phase. The reported temperature corresponded to the liquid phase. The exposure time was approximately 5 years (the actual exposure time is given in Table 4) for TiGr 12 and TiGr 16 and approximately 2.5 years for TiGr 7. The electrolyte solutions were naturally aerated; that is, the solutions were not purged with any gas; however, the ingress of air above the solution level was not restricted. All tests were carried out under ambient pressure. The specimens were tested at the free corrosion potential (E_{corr}), that is, external polarization was not applied. The electrochemical potentials in this paper are reported in the saturated silver chloride scale [SSC]. At ambient temperature, the SSC scale is 199 mV more positive than the normal hydrogen electrode (NHE). After testing, the specimens were studied using standard procedures such as optical and scanning electron microscopy.

RESULTS AND DISCUSSION

Constant Deformation Tests (U -bend Specimens)

The U -bend specimens were exposed to three different multionic electrolyte solutions at the free corrosion potential (E_{corr}) for up to 5 years. Two of these electrolyte solutions (SCW and SDW) were alkaline of $\text{pH} \sim 10$ and one electrolyte (SAW) was acidic of $\text{pH} \sim 3$. One hundred and eighty-two (182) specimens were removed from six of the testing tanks, rinsed in deionized water and allowed to dry in the laboratory atmosphere. Table 4 lists the specimens by their label, by the vessel they were exposed to and by the length of time they were tested. In general, three specimens were examined for each temperature, solution composition and metallurgical condition.

The 182 specimens were first examined optically in a stereomicroscope using up to 100 times magnification. Stereomicroscope studies showed that most of the specimens were completely featureless, that is, they appeared shiny metallic similar to the non-tested condition. Table 5 summarizes the observations for the different tested conditions. Most of the specimens had deposits of crystals (probably salts) from

the electrolyte. The specimens that were exposed to the vapor phase had lower amount of deposits than the specimens exposed to the liquid phase. However, surface features suggest that the specimens exposed to the vapor phase had abundant condensation on them. The specimens that were tested at the highest temperature (90°C) in the liquid phase in general showed higher degree of discoloration than the specimen tested at 60°C. This may suggest that there was more interaction between the specimens and the environment at the highest temperature; however, most of the colors and deposits observed (Table 5) suggest that these were result of buildup from the environment rather than due to a reaction of the metal with the environment. Besides titanium alloys, the tanks listed in Tables 4 and 5 contained a large number of specimens made of nickel alloy such as Alloy 22, C-4, G-3, 825 and 625. The origin of the colors (e.g. golden/green/blue) is not yet known (Figure 2). The golden color was probably caused by the deposit of little crystals of this color on the surface. Some of these small crystals may be rich in iron. Some rust could have come from the dissolution of residual iron material transferred to the specimens and coupons during their mechanical labeling using metal stamps or punches.

Some of the tested TiGr 12 specimens suffered minor corrosion and shallow fissuring, which nucleated from the side of the specimens, not from the apex or top. Some of this minor corrosion and fissuring (Figures 3 and 4B) could have initiated due to the presence of residual material or defects from fabrication tools. None of the TiGr 16 and TiGr 7 specimens suffered environmentally assisted cracking (EAC). Figure 6 are SEM images of two tested TiGr 7 U-bends specimens showing the absence of EAC. Of the 182 examined specimens listed in Table 4, only three suffered environmentally assisted cracking (EAC) or stress corrosion cracking (SCC). These were the welded TiGr 12 specimens exposed to the SCW liquid solution at 90°C (Figure 4A and Figure 5). TiGr 12 in general is less resistant to corrosion than TiGr 7, especially under reducing conditions. For example, Schutz and Grauman measured the critical pitting temperature (CPT) of TiGr 12 and TiGr 7 in 47% MgCl₂ under an applied current density of 200 mA/cm².³⁴ They reported that the CPT of TiGr 12 was 175°C while the CPT of TiGr 7 was higher than 260°C.³⁴ Moreover, TiGr 12 has higher strength and lower ductility than TiGr 7 or Gr 16 (Table 1); which could be detrimental for resistance to EAC. It has also been reported before that TiGr 12 suffered brittle fracture at cathodic applied potentials while TiGr 7 was not embrittled under the same testing conditions.²⁸

At this moment, it is not known if the environmental assisted cracking (EAC) of welded TiGr 12 reported here was a result of stress corrosion cracking (SCC) or hydrogen embrittlement (HE). The corrosion potential (E_{corr}) of titanium alloys under the tested conditions is not known. E_{corr} values for Alloy 22 show that these can range from approximately +0.35 V (SSC) in SAW at 90°C to near 0 V in SCW at 90°C.³⁵ That is, the E_{corr} in SAW, where TiGr 12 did not suffer cracking, was higher than the E_{corr} in SCW, where TiGr 12 did crack. Hence, it is more likely that hydrogen could be discharged in atomic form in the SCW solution, ingress the alloy and therefore cause embrittlement. On the other hand, SCW contained 1400 ppm of fluoride in its composition (Table 3) and SAW did not contain any fluoride. This anion could increase the corrosion rate of Titanium alloys by partially destroying its passivity.²⁰ Additionally, it has been reported that TiGr 7 cracked in a solution containing fluoride ions.³⁰ It is also important to mention that only the welded TiGr 12 specimens cracked in SCW liquid at 90°C. Non-welded specimens that were immersed side by side with the welded specimens were free of EAC (Table 4). This effect could be related to the mechanical properties of the welded seam as compared to a seamless specimen. Welds tend to have higher strength and lower ductility than the base material, therefore becoming more susceptible to EAC.

Results from this testing show that one of the tested Ti alloys suffered cracking in only one environment. TiGr 12 can be considered the least corrosion resistant of the three tested alloys. The Pd containing alloy

loys, both TiGr16 and TiGr7, were free from cracking in all the tested conditions. These results show that non-welded (wrought) and welded TiGr16 and TiGr7 are highly resistant to EAC when exposed to the free corrosion potential in acidic and alkaline multi-ionic solutions that could be representative of concentrated Yucca Mountain groundwater.

RELATIVE CORROSION RESISTANCE OF TITANIUM ALLOYS

As mentioned in the introduction, corrosion resistant titanium alloys have different responses to corrosive environments depending on their alloying elements. Commercially pure titanium or TiGr2 (R50400) practically does not contain any metallic alloying element. TitaniumGr12 contains approximately one percent of both Mo and Ni and TiGr7 contains about 0.15% Pd (Table 2). The small amount of metallic alloying elements in titanium increases its corrosion resistance under acidic reducing conditions by the cathodic modification mechanism. That is, these small amounts of alloying elements shift the corrosion potential of the titanium alloy in the anodic direction favoring its passivation. Metallic alloying elements are not as beneficial under oxidizing conditions since in this case the environment provides the driving force for oxide film formation. On the other hand, the metallic alloying elements also decrease the susceptibility of titanium alloys to crevice corrosion, basically by reducing the corrosion rate of the alloy under the reducing conditions of an active crevice in an occluded cell. It is also commonly accepted that alloys that offer resistance to localized corrosion such as crevice and pitting corrosion are also resistant to stress corrosion cracking; another localized corrosion process. Palladium and other platinum group metals (PGM) seem to be the most beneficial metallic elements to promote the cathodic modification mechanism. That is, for the alloys of interest mentioned in this paper (TiGr7, TiGr16 and TiGr12), TiGr7, with 0.15% Pd (Table 2) would offer the highest corrosion resistance, TiGr16 the intermediate and TiGr12 the lowest since it contains Mo which is not part of PGM. Corrosion rate data for TiGr16 are scarce; therefore the analysis of corrosion rate will be done using TiGr2, Gr12 and Gr7. Figure 7 shows the corrosion rates of TiGr2, Gr12 and Gr7 in boiling dilute solutions of sulfuric and hydrochloric acid (reducing conditions). Due to the beneficial alloying properties of Pd, the corrosion rate of TiGr7 is approximately two orders of magnitude lower than the corrosion rate of TiGr12. Figure 8 shows the corrosion rate of the three titanium alloys in two versions of the same oxidizing acidic solution. The solution mentioned in ASTM G28B contains 23% H_2SO_4 + 1.2% HCl + 1% $FeCl_3$ + 1% $CuCl_2$ and the green death solution contains 11.5% H_2SO_4 + 1.2% HCl + 1% $FeCl_3$ + 1% $CuCl_2$. Figure 8 shows that the corrosion rates of the three titanium alloys are of the same order of magnitude. That is, in oxidizing conditions, the beneficial effects of alloying Pd are diminished. Figure 8 shows also that the corrosion rate of the titanium alloys was higher in the ASTM G28B solution than in the green death environment, probably due to the higher acid concentration in the former.

Wong et al. recently reported corrosion rate data for TiGr12, Gr16 and Gr7 after 5 and 2.5 years immersion tests in SAW, SCE and SDW solutions at 60°C and 90°C.³⁶ In general, TiGr12 exhibited the highest corrosion rates and TiGr7 the lowest. For example, the corrosion rate of creviced TiGr12 in liquid SCW at 90°C was 192 nm/year and the corrosion rate of TiGr7 in the same conditions was 32 nm/year. The most aggressive solution for titanium alloys was SCW (concentrated alkaline) and the least aggressive were SDW (dilute alkaline) and SAW (concentrated acidic).³⁶

CONCLUSIONS

- (1) Mill annealed (MA) or wrought and welded Ti Gr 7 and Ti Gr 16 alloys are highly resistant to environmentally assisted cracking (EAC) in multi-ionic solutions that could be representative of groundwater at Yucca Mountain.
- (2) U-bend samples of Ti Gr 16 exposed at E_{corr} for up to 5 years and Ti Gr 7 exposed for 2.5 years in SAW, SCW and SDW solutions at 60°C and 90°C were free from EAC.
- (3) Welded Ti Gr 12 U-bend specimens suffered EAC in SCW liquid at 90°C. Under the same conditions, non-welded Ti Gr 12 was free from cracking.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U. S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract N° W-7405-Eng-48. This work is supported by the Yucca Mountain Project, which is part of the Office of Civilian Radioactive Waste Management (OCRWM).

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TABLE1
TYPICAL MECHANICAL PROPERTIES OF TITANIUM ALLOY SHEET
(From ASTM B265)

Alloy, UNS	First Letter Notation for Specifications	Tensile Strength min. [UTS] (MPa)	Yield Stress [0.2%] min. (MPa)	Elongation to Rupture min. (%)
TiGr7, R52400	N	345	275	20
TiGr 16, R52402	F	345	275	20
TiGr12, R53400	E	483	345	18

NA=Not Available

TABLE2
CHEMICAL COMPOSITION OF TITANIUM ALLOYS (Wt%)

	TiGr7 Base Metal	TiGr7 Weld Filler	TiGr16 Base Metal	TiGr16 Weld Filler	TiGr12 Base Metal	TiGr12 Weld Filler
Heat	R3928	BN4591	X-52020	5D3438	BN2966	AT7879
C	0.07	0.008	0.013	0.008	0.05	0.006
H	0.003	0.002	0.0048	0.0063	0.002	0.0044
Fe	0.18	0.02	0.11	0.04	0.07	0.12
Mo	---	---	---	---	0.36	0.3
N	0.011	0.008	0.006	0.002	0.02	0.004
Ni	---	---	---	---	0.78	0.82
O	0.12	0.037	0.14	0.12	0.14	0.08
Pd	0.16	0.17	0.07	0.19	---	---
Ti	>99	>99	>99	>99	>98	>98

TABLE3
CHEMICAL COMPOSITION OF THE ELECTROLYTE SOLUTIONS (mg/L)

Ion	SDW pH10.1	SCW pH10.3	SAW pH2.8	J-13 Well Water pH7.4
K ⁺	34	3400	3400	5.04
Na ⁺	409	40,900	40,900	45.8
Mg ²⁺	1	<1	1000	2.01
Ca ²⁺	0.5	<1	1000	13
F ⁻	14	1400	0	2.18
Cl ⁻	67	6700	24,250	7.14
NO ₃ ⁻	64	6400	23,000	8.78
SO ₄ ²⁻	167	16,700	38,600	18.4
HCO ₃ ⁻	947	70,000	0	128.9
SiO ₂ (aq)	~40	~40	~40	61.1

TABLE4
LIST OF CONSTANT DEF OR MATION (U -BEND) EX AMINED SPECIMENS

	SAW, 60°C	SAW, 90°C	SCW, 60°C	SCW, 90°C	SDW, 60°C	SDW, 90°C
Vessel	25	26	27	28	29	30
Date in	06Feb1997	21Feb1997	10Mar1997	10Apr1997	14Apr1997	05Jun1997
Date out	20May2002	21May2002	17May2002	22May2002	10May2002	22May2002
Exposure Time, days(h)	1930 (46,320h)	1916 (45,984h)	1895 (45,480h)	1869 (44,856h)	1853 (44,472h)	1813 (43,512h)
Gr7 Date in	20Dec1999	16Dec1999	19Dec1999	14Dec1999	09Dec1999	07Dec1999
Gr7 Date out	20May2002	21May2002	17May2002	22May2002	21May2002	22May2002
Gr7 Exp osure Time, days(h)	882 (21,168h)	887 (21,288h)	883 (21,192h)	890 (21,360h)	894 (21,456h)	897 (21,528h)
Wrought - V a- porPhase	NUA001-003 FUA019-021 EUA019-021	NUA031-033 FUA049-051 EUA049-051	NUA061-063 FUA079-081 EUA079-081	NUA091-093 FUA109-111 EUA109-111	NUA121-123 FUA127 EUA127	NUA151-153 FUA139 EUA139
Wrought - LiquidPhase	NUA028-030 FUA022-024 EUA022-024	NUA058-060 FUA052-054 EUA052-054	NUA088-090 FUA082-084 EUA082-084	NUA118-120 FUA112-114 EUA112-114	NUA148-150 FUA128 EUA128	NUA178-180 FUA140 EUA140
Welded- V a- porPhase	NUE013-015 FUE019-021 EUD019-021	NUE043-045 FUE049-051 EUD049-051	NUE073-075 FUE079-081 EUD079-081	NUE103-105 FUE109-111 EUD109-111	NUE133-135 FUE127 EUD127	NUE163-165 FUE139 EUD139
Welded- Li q- uidPhase	NUE016-018 FUE022-024 EUD022-024	NUE046-048 FUE052-054 EUD052-054	NUE076-078 FUE082-084 EUD082-084	NUE106-108 FUE112-114 EUD112-114*	NUE136-138 FUE128 EUD128	NUE166-168 FUE140 EUD140
Total Exa m- ined Spec i- mens	36	36	36	36	20	20
Total Cracked	0	0	0	3	0	0

*These are the only specimens that cracked.

TABLE 5
STEREOMICROSCOPE OBSERVATIONS OF THE TETES TEDU -BEND SPECIMENS

Conditions	Vapor Phase	Liquid Phase
Vessel 25 SAW, 60°C	Shiny gray metallic. Few isolated brown deposits. Some corrosion on edges for Gr 12. No cracking	Shiny gray -green or light golden. Small amount of brown deposits. No corrosion. No cracking
Vessel 26 SAW, 90°C	Shiny metallic light gray or bluish. Brown deposits in concave area. No corrosion. No cracking	Golden brown with a green tint. Some fissures from edges on TiGr 12. No corrosion. No cracking
Vessel 27 SCW, 60°C	Shiny and dull light gray with bluish and golden patches. White deposits. No corrosion. No cracking	Shiny light golden and gray. Shallow cracks from side and corrosion on leg ends (Gr 12). No corrosion. No cracking
Vessel 28 SCW, 90°C	Shiny dark gray and golden. Little white and green deposits in concave area. No corrosion. No cracking	Sample covered by white deposits. No apparent corrosion. No cracking. <u>Welded TiGr 12 Cracked (EAC).</u>
Vessel 29 SDW, 60°C	Shiny light gray and golden. Little corrosion at end of legs for Gr 12. No cracking	Shiny light gray and golden. Little corrosion from sides for Gr 12. No cracking
Vessel 30 SDW, 90°C	Shiny gray and light golden. Little corrosion from sides for Gr 12. No cracking	Shiny gray, blue and golden. Shallow corrosion from sides for Gr 12. No cracking

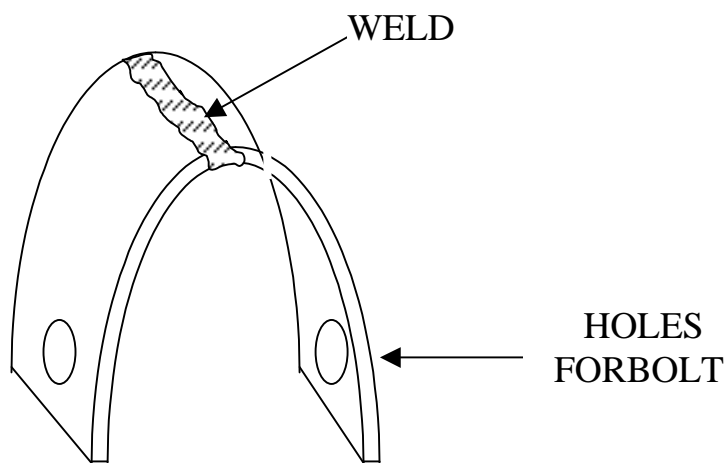
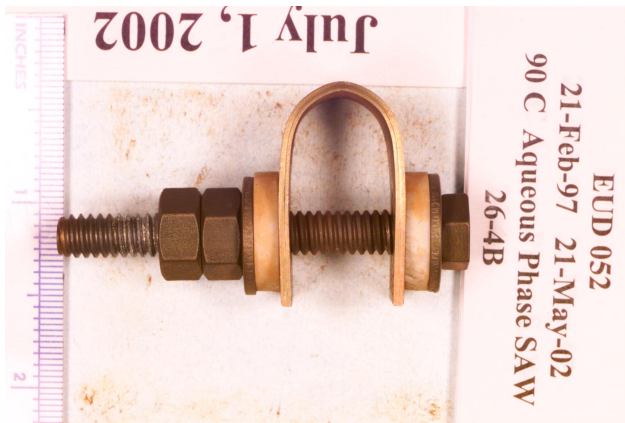
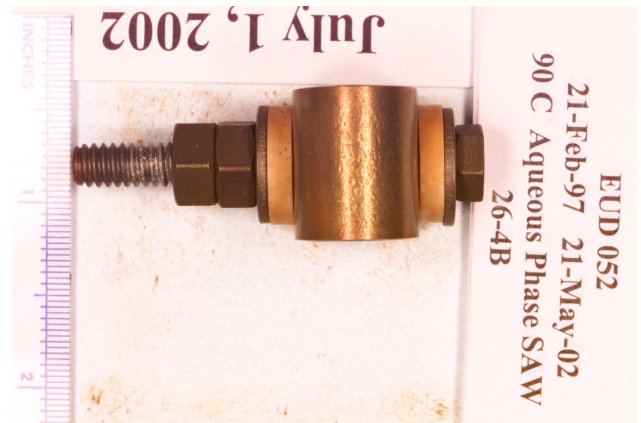


FIGURE 1: Schematic representation of the welded U-bend specimens.

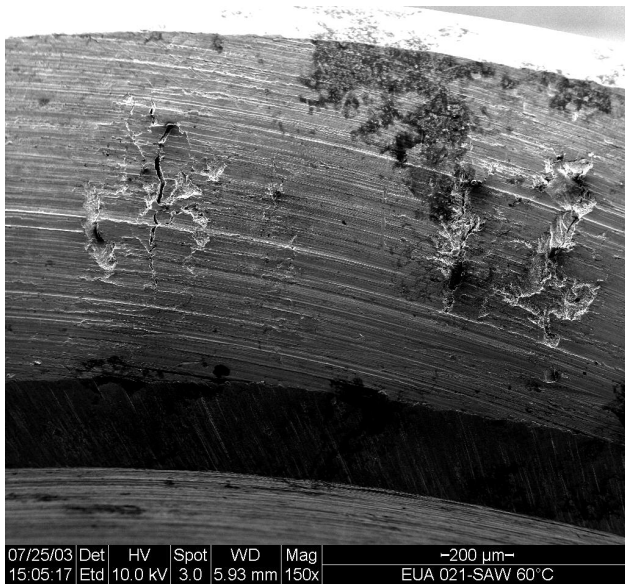


A

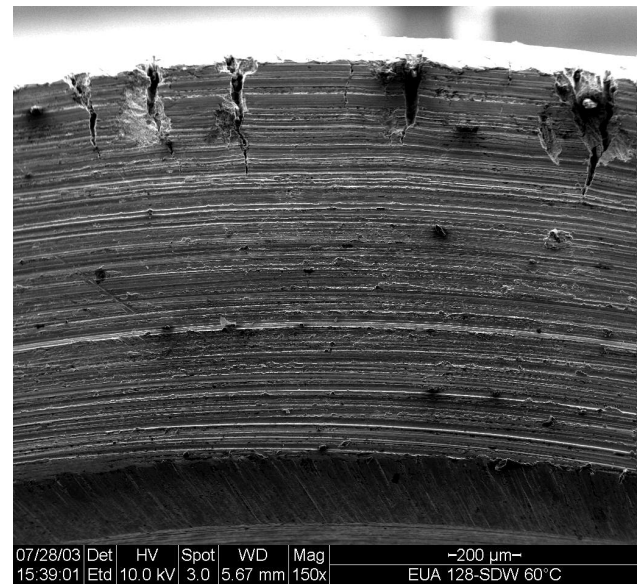


B

FIGURE2: Welded TiGr12 exposed for 5+ years in SAW liquid at 90°C, (A) Side view and (B) top or apex view. The specimen is free from cracking.

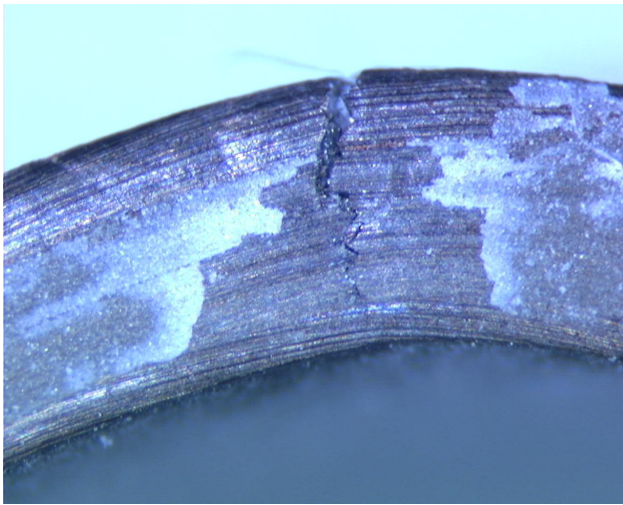


A

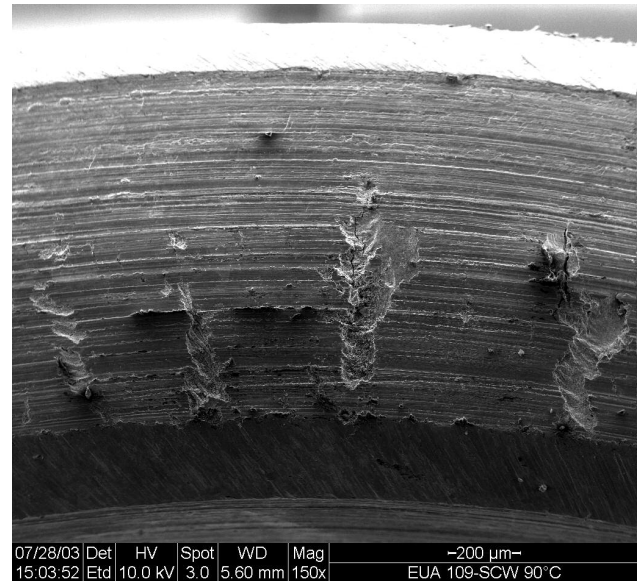


B

FIGURE3: Side view of non-welded TiGr12U bend specimen exposed for 5+ years in the LTCTF. (A) EUA021 in SAW vapor at 60°C, 150X Magnification and (B) EUA128 in SDW liquid at 60°C, 150X Magnification. The specimen suffered minor fissuring.



A



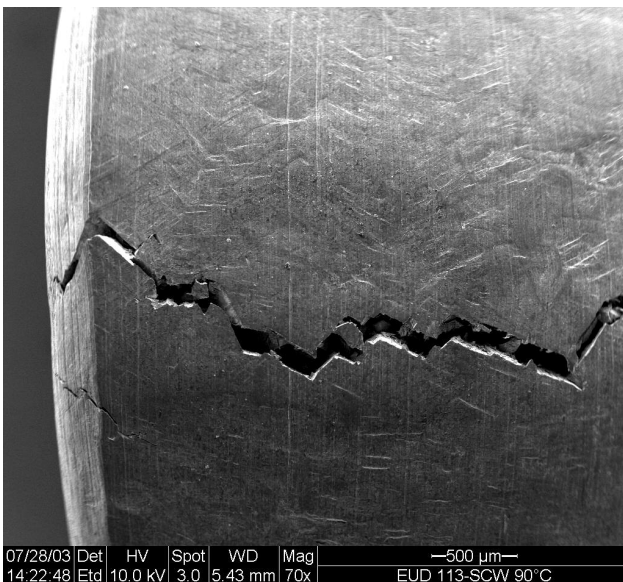
B

FIGURE4:Sideviewofnon -weldedTiGr12U -bendspecimensexposedfor5+yearsintheltctf.

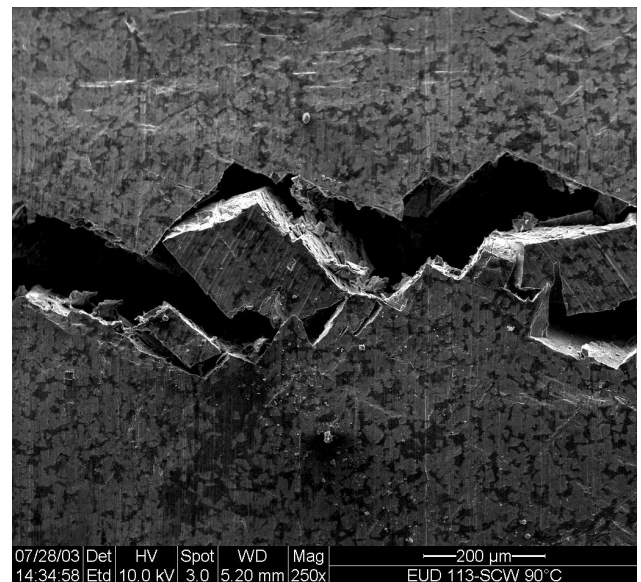
(A)EUD112inSCWliquidat90°C,approximatelyX20Magnificationand

(B)EUA109inSCWvaporat90°C,X150Magnification

OnlytheweldedTiGr 12specimensinexposedtotheliquidphaseofSCWat90°Csufferedsevere cracking(Figure5).Thenonweldedspecimenintheliquidphasesufferedminorfi ssuring.



A



B

FIGURE5:Topview(apex)SEMimagesofweldedTiGr12(EUD113)exposed for5+yearsinscw

liquidat90°C.(A)X70Magnificationand(B)X250Magnification.

Thespecimensufferedenvironmentallyassistedcracking.

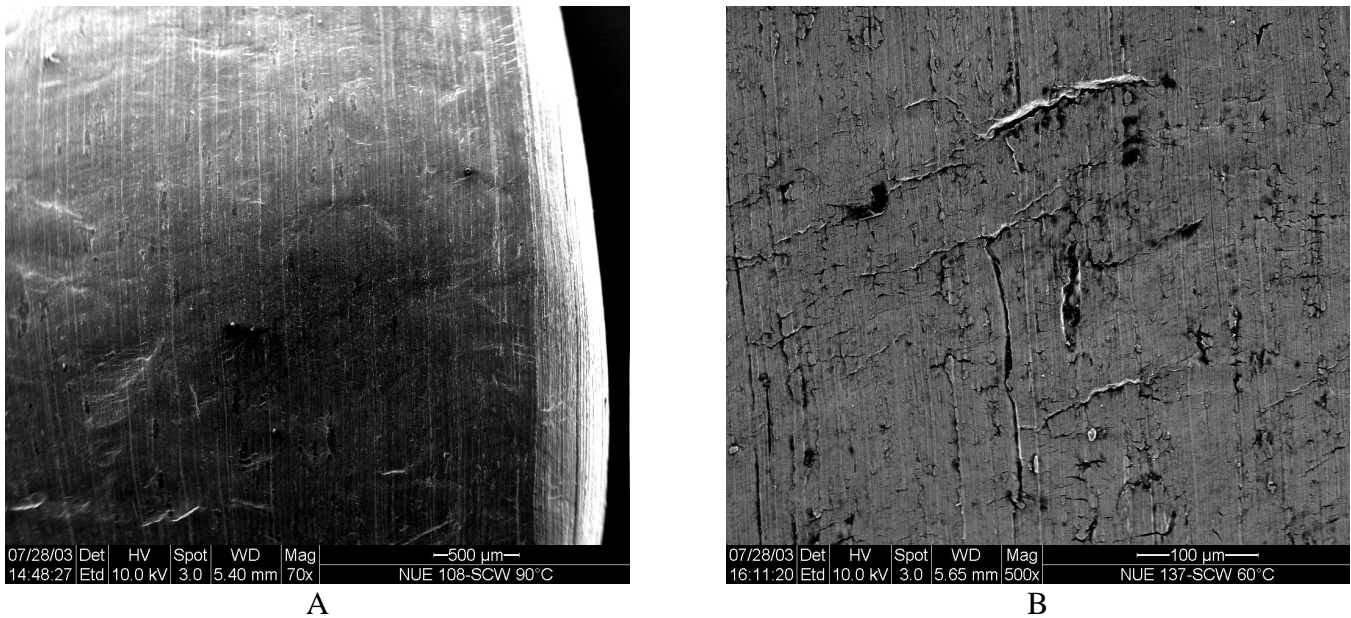


FIGURE6:Topview(apex)ofweldedTiGr7U -bendspecimensexposedfor2.5+yearsinthelTCTF.
 (A)NUE108inSCWliquidat90°C,X70Magnification,and
 (B)NUE137inSDWliquidat60°C,X500Magnification.

Allthenon- weldedandweldedTiGr7specimenswerefreefromenvironmentallyassistedcrackingin
 allthetestedenvironments.Someminor fissuringobservedintheapexispre- existenttotesting.

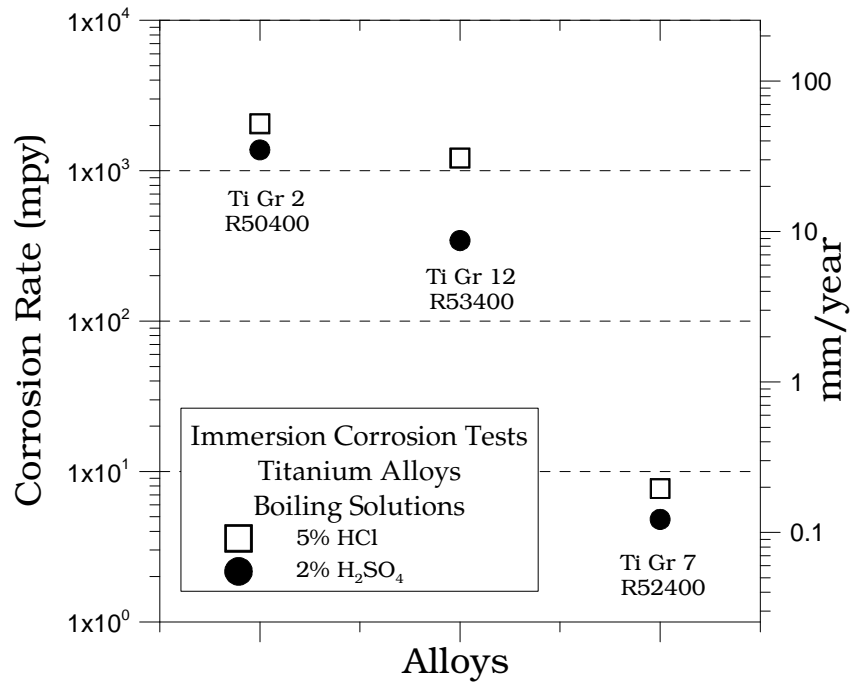


FIGURE7:CorrosionRateofTialloysinreducingacidicconditions.
 ThecorrosionrateofTiGr7is severaloordersofmagnitudelowerthanthe corrosionrateof
 DatafromHaynesInternationalandReference5.

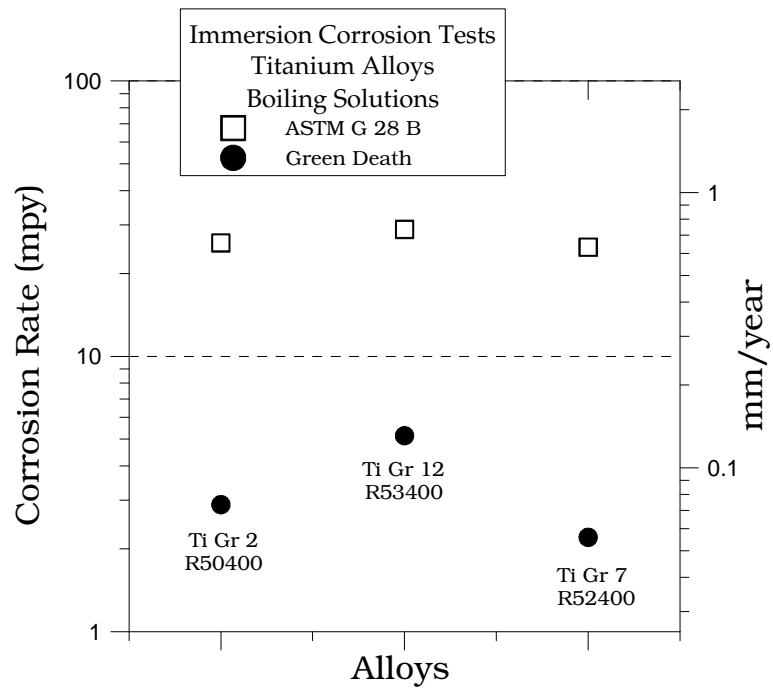


FIGURE 8: Corrosion Rate of Ti alloys in oxidizing acidic conditions. ASTM G 28 B contains 23% H_2SO_4 + 1.2% HCl + 1% FeCl_3 + 1% CuCl_2 and the green death solution contains 11.5% H_2SO_4 + 1.2% HCl + 1% FeCl_3 + 1% CuCl_2 . In both solutions, the corrosion rates of Ti Gr 7 and Ti Gr 12 are comparable. Data from Haynes International and Reference 5.